

## Article

# Gassing Tendency of Fresh and Aged Mineral Oil and Ester Fluids under Electrical and Thermal Fault Conditions

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**Abstract:** Operational factors are known to affect the health of an in-service power transformer and to reduce the capabilities and readiness for energy transmission and distribution. Hence, it is important to understand the degradation rate and corresponding behavioral aspects of different insulating fluids under various fault conditions. In this article, the behavior of mineral oil and two environmentally friendly fluids (a synthetic and a natural ester) are reported under arcing, partial discharges, and thermal fault conditions. Arcing, partial discharges and thermal faults are simulated by 100 repeated breakdowns, top oil electrical discharge of 9 kV for five hours, and local hotspots respectively by using different laboratory-based setups. Some physicochemical properties along with the gassing tendency of fresh and aged insulating liquids are investigated after the different fault conditions. UV spectroscopy and turbidity measurements are used to report the degradation behavior and dissolved gas analysis is used to understand the gassing tendency. The changes in the degradation rate of oil under the influence of various faults and the corresponding dissolved gasses generated are analyzed. The fault gas generations are diagnosed by Duval's triangle and pentagon methods for mineral and non-mineral oils. It is inferred that; the gassing tendency of the dielectric fluids evolve with respect to the degradation rate and is dependent on the intensity and type of fault.

**Keywords:** transformer; insulating liquids; ester fluids

## 1. Introduction

Alternative dielectric fluids for use in oil-filled apparatuses is a topic of concern for industry and utilities for decades. Ester dielectric fluids (both natural and synthetic esters) are being investigated for use in oil-filled transformers. The dielectric properties and rate of deterioration of ester fluids is comparable to those of mineral insulation oils used in power transformers [1]. The compatibility of these alternative fluids with solid insulants was investigated and reported possible longevity of cellulose insulants when used with ester dielectric fluids [2]. The pre-breakdown phenomena, workability, influence of temperature, compatibility with other transformer materials, and service experience were reported by various researchers [1,3–5]. Several researchers also attempted to understand the regeneration aspects and end of life criteria of these insulating fluids [6]. From the extensive laboratory studies, IEEE Standards and CIGRE reports came to the acceptance of using these fluids in oil-filled transformers [7–9]. However, condition monitoring and diagnostic tools for ester-filled transformers is still a topic of high interest for the industry. Meanwhile, the possibility of ester fluids to be miscible with mineral insulating oils was a topic of research to understand the feasibility of retro filling existing units. Fofana et al. [10,11] reported the properties of various mixtures of mineral oil and ester fluids extensively. Later, U. Mohan Rao et al. [12,13] reported the long-term degradation

behavior, degradation solid insulation in mixture insulating fluids. Nevertheless, ester fluids are being used in oil-filled transformers and various utilities across the globe started filling/retrofilling some new and existing transformers with ester liquids. There is a large scope for research including, but not limited to, the understanding of the behavior of these insulating fluids under different operating conditions, regeneration aspects, and condition monitoring aspects.

Despite due care is taken by manufacturers and utility, yet there is a high probability for electrical discharges and local hotspots. The presence of electrical discharges and local hotspots for longer duration leads to high electrical discharge and thermal failures. The electrical faults are low and high-energy discharge electrical faults, which are treated as corona discharges, partial discharges, and breakdown. Thermal faults are the accumulation of heat over a local area and are treated as hotspots. Both electrical and thermal faults are originated because of various reasons including, dielectric defects, air bubbles, impurities, sharp edges, and any manufacturing defects. The presence of these faults hampers the integrity of the insulation system in various aspects and is detrimental to a transformer. Therefore, early detection of these faults is of high importance to condition monitoring engineers and maintenance planners. It is well established that, these faults are involved in the generation of several gasses that are dissolved in the oil. Therefore, the dissolved gas analysis is seen as one of the important conditions monitoring and diagnosis tools.

Numerous researchers have reported the gassing tendency of various dielectric liquids under different fault conditions. The tendency to gassing generation under partial discharges or low energy discharge electric faults in mineral oils and ester fluids were investigated and reported in [14–16]. It is reported that higher quantities of  $C_2H_2$  and  $H_2$  are generated in natural esters and  $C_2H_2$  remains the key gas to indicate a defect or fault witnessed by electrical discharges. Also, the influence of high energy discharges on the gassing tendency of the dielectric fluids have been reported in [14,17,18]. Similar to the low energy discharge faults,  $H_2$  and  $C_2H_2$  are found to be witnessed due to arcing fault conditions. However, a large amount of  $C_2H_2$  is generated as compared to the low energy discharge cases. The gassing tendency of ester fluids under thermal faulty condition was also investigated and are reported in [14,15,18–20]. It is found that natural ester generates more gases at a higher temperature ( $>300\text{ }^\circ\text{C}$ ) and traces of  $C_2H_6$  are found increasing with increasing temperature. The key gasses in ester fluids under thermal faults are found to be  $CH_4$ ,  $C_2H_4$ ,  $CO$ , and  $C_2H_6$ . However, there are different methods for simulating the hotspot at different temperatures; the gassing tendency of the dielectric fluid varies accordingly. The details are critically analyzed and summarized in [21]. It is to be mentioned that, the fault diagnosis approaches discussed above are limited to a single fault i.e., electrical or thermal fault alone. However, in the real transformer, there are possibilities for the electrical and thermal faults to occur simultaneously. Thus, in [22] a combination of electrical and thermal faults was studied. The authors reported the gassing tendency at different combinations of electrical and thermal faults while varying fault temperatures and fault voltages. The trending of fault gasses has been explicitly reported under different laboratory conditions.

Electrical discharges, electrical arcing, and thermal faults in a transformer influence the degradation of the oil accompanied by faults gas generations. These faults also, expedite the degradation reactions in a transformer, which together with acids and heat accelerate deterioration of the insulation system. It is to be understood that the intensity of this degradation process and fault gasses are also attributable to the condition of the oil. In other words, the occurrence of the same fault with the dielectric fluid at two different conditions (age) will have different levels of consequences. Recently, authors from our research group have reported the influence of aging on the gassing tendency and oil's degradation under low energy electrical discharge faults for mineral oil and synthetic esters [23].

It was reported that the condition (age) of the oil has a significant influence on the concentration of the dissolved gases which affects the fault diagnostic conditions. Also, the influence of thermal aging on the gassing tendency of mineral oil and natural esters under the influence of thermal faults has been reported in [19]. A significant change in the dissolved gas concentration has been noticed with an increase in the thermal aging duration of the dielectric fluids. Hence, there is a need to study

the gassing behavior of ester-based dielectric fluids (both natural and ester) under the influence of electrical and thermal fault conditions at different aging conditions and the influence of the faults on oil degradation. Therefore, the present research is aimed to understand the influence of aging or state of the dielectric liquid on gassing tendency under different operating faulty conditions. The authors have also focused the influence of different faults on the degradation of the dielectric fluids. In the present work a mineral oil, a synthetic ester, and a natural ester have been investigated under low electrical energy discharge, high electrical energy arcing, and hotspot faulty conditions. The degradation of the insulation liquids is monitored by adopting UV spectroscopy and turbidity measurements as per ASTM D6802 and ASTM D6181 standard test methods respectively. The dissolved gas analysis measurements are performed as per ASTM D3612.

## 2. Experimental

### 2.1. Samples

For the present study, a mineral oil (MO), a natural ester (NE), and a synthetic ester (SE) have been adopted. The properties of the fresh unused oils considered for this study are tabulated in Table 1.

**Table 1.** Significant properties of the unused base oils used in this study.

Parameters	MO	NE	SE
Power Factor 50 Hz 90 °C, IEC 60247	<0.001	–	<0.008
Water content (ppm), IEC 60814	<20	<50	<50
Viscosity (cSt @ 40 °C), ISO 3104	9.2	32	29
Fire point (°C), ISO 2592	–	>350	316
Flash point (°C), ISO 2719	148	>260	260
Pour Point (°C), ISO 3016	–54	–18	–56
Acidity, (mg KOH/g), IEC 62021	<0.01	<0.04	<0.03
Density at 20 °C (kg/dm <sup>3</sup> )	0.869	0.92	0.97

Unused mineral oil, synthetic ester, and natural ester have been subjected to thermal aging according to a modified ASTM D1934 standard method at 115 °C for 2000 h. The thermal aging is performed with the copper catalyst (3 g/L) and cellulose Kraft papers (1:20). After the thermal degradation procedure, highly degraded oil/paper insulation is subjected to sonication for 30 s using Qsonica Q1375 Sonicator. This sonication allowed to prepare a gentle solution of degraded oil and paper. Further, the individual solutions of MO, NE, and SE are separately added to unused MO, NE, and SE respectively. The proportions of the degraded solution added to unused oils allowed controlling the acid values of the oils. This facilitated having oil samples with a specific level of acidity that refers to a bad class of the oil aging as per [24].

It is to be mentioned that attaining a predetermined value of acidity is not feasible with the traditional thermal aging process. Therefore, the authors prepared a degraded solution which is later used to obtain a specific value of the acidity by adding it in suitable proportions. Now, these aged oils (obtained with the desired acidity values) along with fresh unused oils are used for the present study. The details of the acidity measurements of the bad class are illustrated in Table 2.

**Table 2.** Details of acidity measurements of bad class insulating liquids.

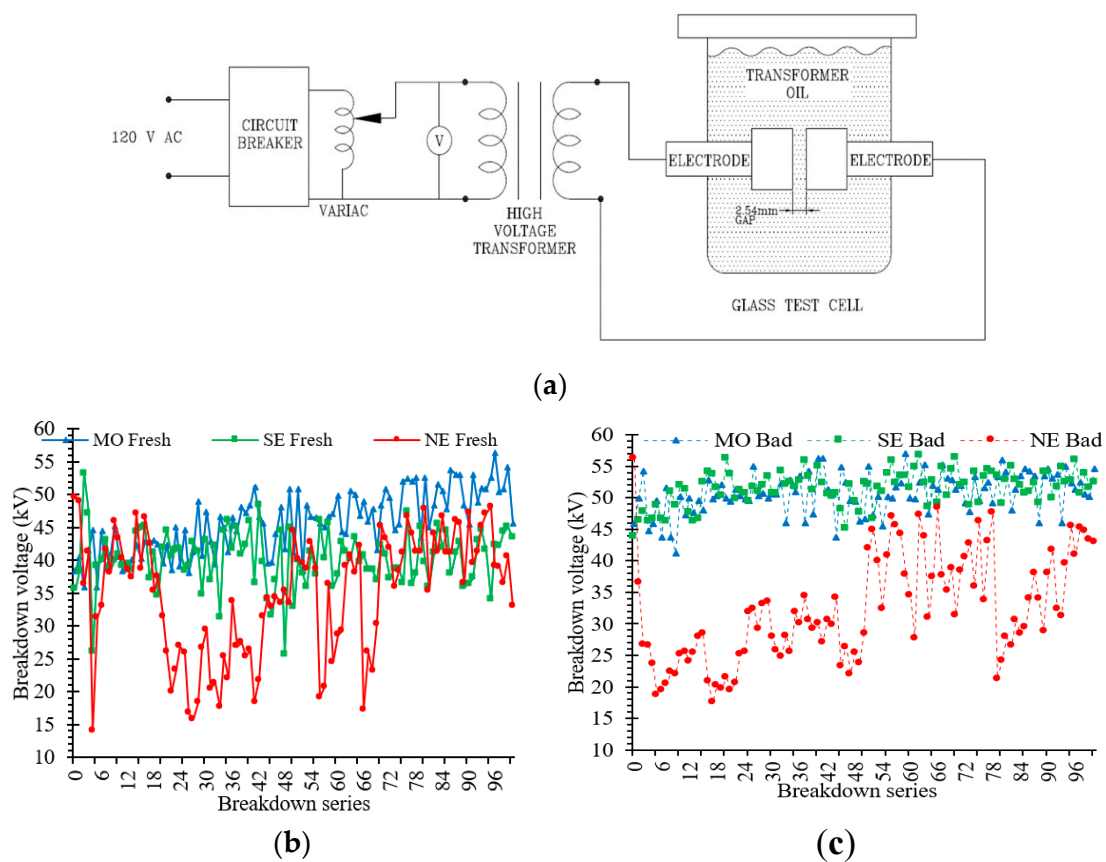
Sample	Acidity Test 1 mg KOH/g	Acidity Test 2 mg KOH/g	Average	Std. Deviation	Ratio of Degraded Solution to Fresh Oil *
MO Bad Class	0.2757	0.2675	0.2716	0.0058	1:26.6
SE Bad Class	0.2314	0.2573	0.24435	0.0183	1:20
NE Bad Class	0.3016	0.2801	0.29085	0.0152	1:40

\* ratio adopted for this study.

## 2.2. Laboratory Simulation of Electrical and Thermal Faults

### 2.2.1. High Energy Discharges (Arcing)

High energy discharge faults are stimulated by repeated breakdowns to produce arcing in the oil volume. The breakdown of the insulation fluid is performed in the laboratory as per ASTM D 877. To simulate the sustainability of the arcing fault, 100 breakdowns have been performed with 2 min of break between each breakdown. To understand the impact of high-energy discharge electrical faults, dissolved gas analysis is performed after 100 continuous breakdowns. To understand the influence on oil degradation, UV spectroscopy and turbidity measurements are reported before and after 100 breakdowns. The details of the breakdown test set up are presented in Figure 1a and the series of breakdowns for MO, NE, and SE for fresh and aged oils are shown in Figure 1b. In addition, the total average energy used for 100 breakdowns in various liquids is tabulated in Table 3.



**Figure 1.** Experimental of the arcing fault in various dielectric fluids; (a) test set up used for arcing; (b) 100 BDV series for fresh insulating liquids; (c) 100 BDV series for aged insulating liquids.

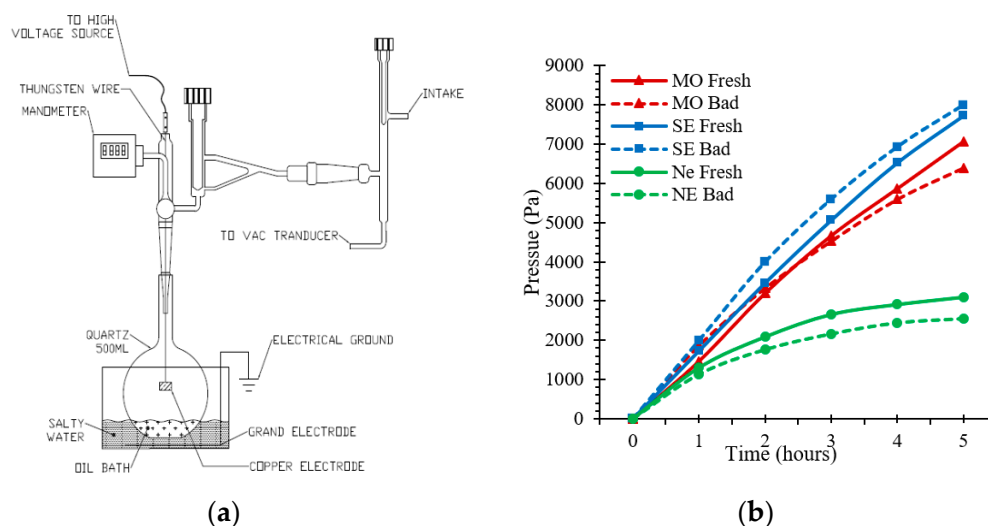
**Table 3.** Details of energy for 100 BDV's.

Sample	MO Fresh	MO Bad	SE Fresh	SE Bad	NE Fresh	NE Bad
Average energy used for 100 BDV's (Joules)	$4.53 \times 10^{-1}$	$5.53 \times 10^{-1}$	$4.40 \times 10^{-1}$	$7.11 \times 10^{-1}$	$3.50 \times 10^{-1}$	$2.97 \times 10^{-1}$

It is observed that, breakdown of the dielectric liquids is increasing with aging and with the number of breakdowns. To understand this, it is to be recalled that water saturation limit of dielectric liquids increases with increase in aging [25]. Also, breakdown voltage is dependent on relative moisture content and hence breakdown voltage of the aged oil will be higher than that of the fresh oil at a given absolute moisture content. Under AC stress, a field-induced drift of particles, located in high field regions, can be entailed by a stress relieve leading to an improvement of the dielectric strength, compared to technically clean oil [26]. In the same way, breakdowns cause definite degradation; this will lead to an increase in the water saturation on average with breakdown times.

### 2.2.2. Low Energy Discharges (Partial Discharges)

Low energy discharges electrical faults are often called partial discharges, which could be internal discharge, surface discharge, and corona discharges. In the present work, a laboratory set up has been used to produce a surface discharge of 9 kV. A 9 kV electrical discharging activity is simulated for 5 h on the surface of the dielectric fluid. The free electrons are generated by a cylindrical copper electrode sealed in a 500 mL Erlenmeyer glass. The electrode is placed in the center of the discharge cell and suspended above the oil's surface. The distance between the central electrode and the surface of oil is approximately one inch. The details of the experimental set-up was reported by the authors from our research group in [23] and is shown in Figure 2a. The discharge is initiated after vacuuming the test cell and the changes in the pressure with discharging time are recorded to understand the gassing behavior of the insulating fluid. This method is useful in understanding the stability of the insulating fluids to gassing behavior. The pressure changes in the test cell with fresh and aged MO, NE, and SE as a function of discharging time are shown in Figure 2.

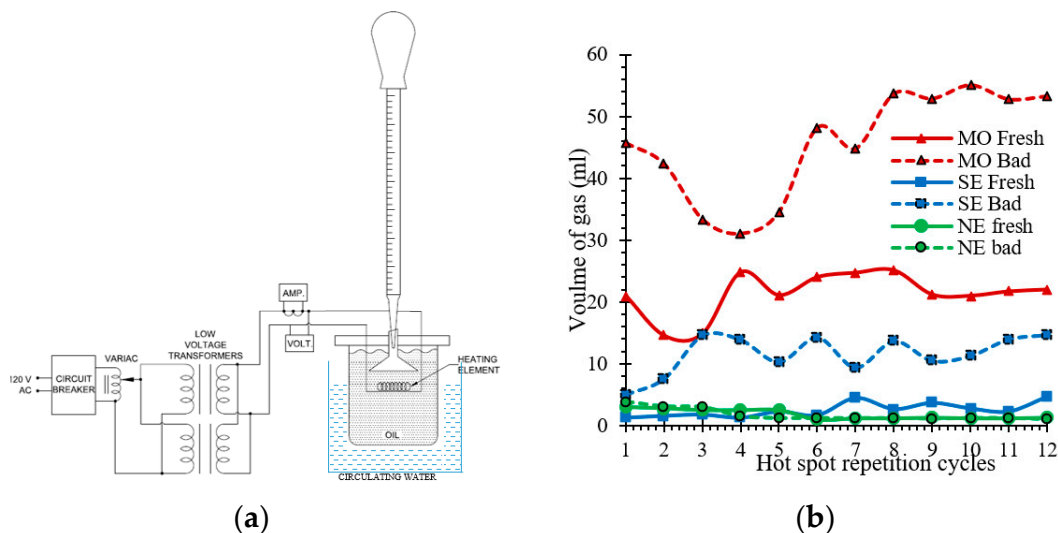


**Figure 2.** Experimental of the low energy discharge activity in various dielectric fluids; (a) test set up used for low energy discharging; (b) gassing tendencies for fresh and aged fluids under electrical discharges.

### 2.2.3. Thermal Faults (Hotspot)

Thermal faults or hotspots simulation in MO, NE, and SE have been simulated by developing a laboratory-based test set up. The setup used for simulating thermal faults is presented in Figure 3a.

The set up consists of a borosilicate-glass vessel and a Teflon cover with bushings to hold the heating element. Constantan was chosen for the heating element for its flat resistivity on a large scale of temperature. The input supply is connected to a variac that feeds two high current transformers connected in parallel while the temperature of the wire was regulated by an ammeter and voltmeter connected between the heating element and the secondary. By measuring the voltage and current, the average temperature of the hotspot may be approximated. This is also validated by using a high-temperature resistant thermocouple. An aluminum funnel-shaped structure is placed just over the heating element. This is because the generated gas bubble enters the pipette through this funnel structure according to the Archimedes' principle where they can be measured. In each experiment, a quantity of 800 mL of dielectric fluid was introduced to fulfil the vessel and the pipette up to the reference value. The fluid samples under hot-spot tests are allowed to heat for periods of 30 min and the volume of gas generated is recorded. The temperature reached values close to 250 °C, which for the mineral is risky because of its flashpoint. For safety reasons, the current is zeroed until the temperature of the insulating fluid equals the room temperature (~24 °C). This test cycle of 30 min of heating and cooling down to room temperature have been repeated for 12 times. For every 30 min of the heating cycle, the volume of gas is recorded. The volumes of the gases generated as a function of the heating cycles are presented in Figure 3b.



**Figure 3.** Experimental of the hotspot fault in various dielectric fluids; (a) test set up used for hotspot; (b) gassing tendency under hotspot condition.

### 3. Results and Discussions

The results of the degradation rate of the oil, before and after simulating electrical and thermal faults are discussed in this section. As mentioned earlier, the degradation of the insulating liquids has been understood by ultraviolet visible spectral curves, dissolved decay contents, and turbidity. The details of the fault gasses evolved because of the characteristic faults have been analyzed by dissolved gas analysis and application of Duval's diagnostic methods reported in the literature. To have a clear observation and to avoid direct comparison of various insulating oils, the authors have presented the results oil by oil with all types of faults. Also, it is difficult to obtain similar level of the fault intensity in order to compare fault by fault. Therefore, it is interesting to see the impact of the same type of faults in a dielectric fluid at different aging conditions (Fresh and Bad classes). The following notations presented in Table 4 are used for representing different cases of the insulating liquids.



**Table 4.** List of abbreviations.

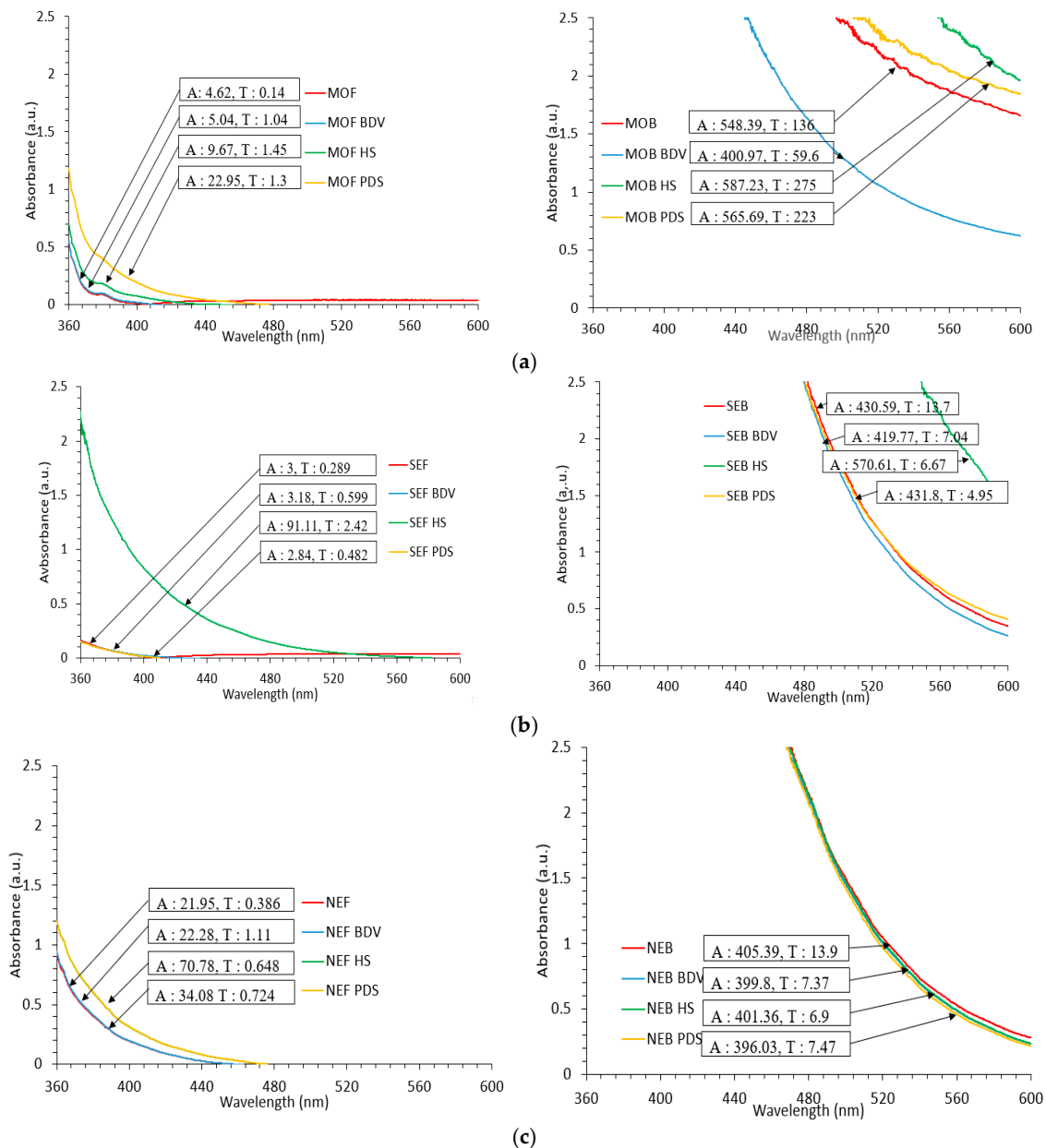
Abbreviation	Details
MOF	Mineral Oil Fresh
MOB	Mineral Ester Bad
SEF	Synthetic Ester Fresh
SEB	Synthetic Ester Bad
NEF	Natural Ester Fresh
NEB	Natural Ester Bad
BDV	High energy discharge (arcing)
PDS	Low energy discharge (Partial discharge)
HS	Hot spot (Thermal fault)
A	Dissolved decay products
T	Turbidity
TDCG	Total dissolved combustible gasses

### 3.1. Degradation of Insulating Fluids

In the present section, the degradation of fresh and aged oils while subjected to electrical and thermal faults is of concern. Fresh oils are technically clean and are free from decay particles and cellulose particles, and other aging byproducts. Whereas, aged oils contain, cellulose particles, dissolved decay products, acids, and other aging byproducts. Therefore, when a fresh oil and aged oil are subjected to different fault conditions, the undergoing chemical perspectives are expected to be different. Subsequently, the influence of these faults on the dielectric fluids will be different. Hence oil absorbance, dissolved decay products, and turbidity are measured for before and after subjecting the liquids to the fault conditions. The details have been presented in Figure 4.

In fresh oils, the changes that occur because of the application of thermal and electrical faults depend majorly on the thermal stability of the chemical bonds and the ionization potential respectively. In case of aged oils, along with the said factors, the concentration of colloidal and soluble decay particles plays a significant role in further degrading a dielectric fluid. Therefore, in the present research, the concentration of the dissolved decay products and turbidity measurements have been reported. From Figure 4, it is seen that aged oils have a high turbidity, decay content concentration which is obvious. It is to be noticed that, the application of fault conditions (both electrical and thermal) had a different impact for fresh and aged oils. In Figure 4a, from fresh mineral oil, the influence of partial discharges is high as compared to arcing and hotspot. Similarly, in the case of aged oils, the hotspot influence is superior to that of the partial discharges and arcing. However, it is seen that the absorbance of aged oil is reduced with arcing. This may be due to the splitting or de-agglomeration of the cellulose particles present in the oil which reduces the absorption to light. To further understand this, the chemical function group analysis is to be understood. The absorbance and turbidity of the aged oil are increasing with partial discharges and thermal faults. From Figure 4b, it is noticed that, the influence of hotspot is higher than that of the partial discharges and arcing for fresh and aged synthetic esters. Also, the influence of partial discharges and arcing is too low in the case of fresh and aged fluid samples. One may understand that, the influence of electric faults is low when compared to thermal faults in the case of synthetic esters. However, it is to be assured that, the intensity of the fault nature is uniform in all three cases. Also, in Figure 4c, the influence of the hotspot is higher when compared to the other faults in the case of fresh natural esters. To understand the influence, faults of much higher intensities are to be evaluated. It is to be recalled that, thermal faults involve an increase in local temperature and promoting oxidation of the oil/paper insulation. These generated acids trigger a self-sustained process called hydrolysis which in turn degrades the solid insulation. But, in case of electrical faults,

the influence is more associated to a generation of acids and free radicals which leads the degradation. However, both electrical and thermal faults are involved with the generation of dissolved gasses. The detailed analysis of dissolved gas analysis is presented in the next section.



**Figure 4.** Illustration of the degradation of the investigated dielectric fluids under different fault conditions; (a) mineral oil; (b) synthetic ester; (c) natural ester.

### 3.2. Gassing Tendency of Insulating Fluids

The dissolved gas analysis for mineral oil and non-mineral oils are analyzed according to IEEE C57.104 and IEEE C57.155 respectively. As per of IEEE C57.104 and IEEE C57.155 the following are the observation on gas trending in mineral oil and non-mineral oils respectively for different fault conditions.

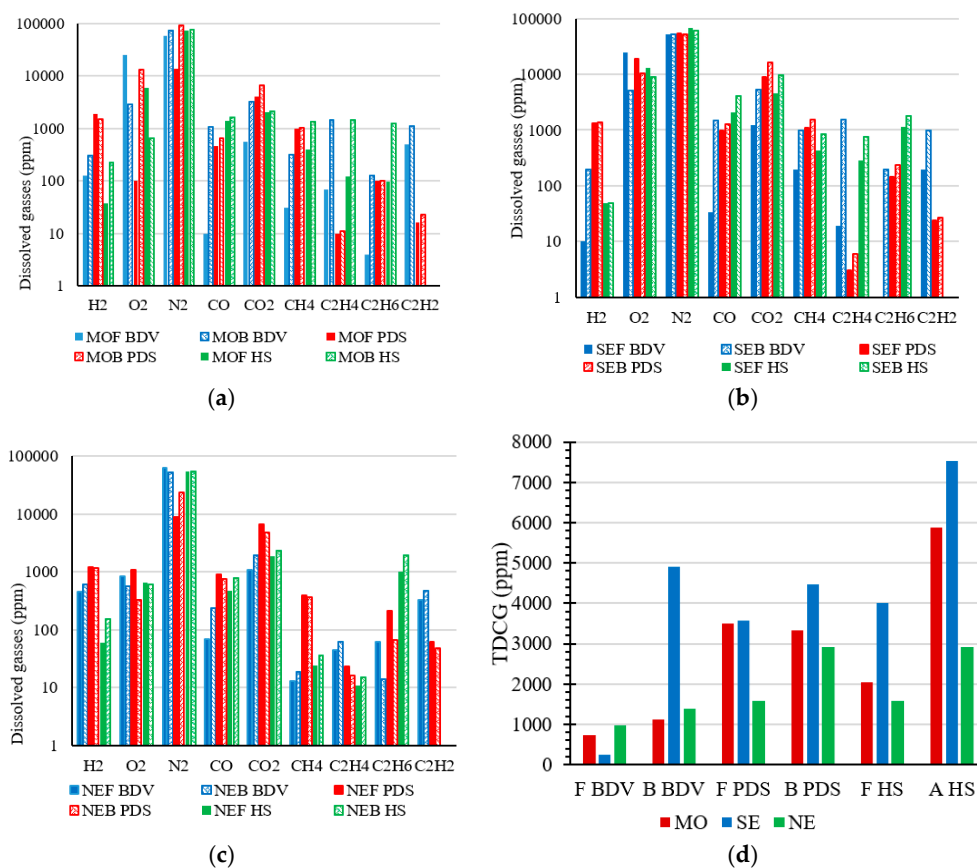
**Arcing faults:** With high energy discharges, traces of  $C_6H_2$  and  $C_2H_6$  increase in mineral oils and  $C_2H_6$  is generated in ester fluids. However,  $H_2$ ,  $CH_4$ ,  $C_2H_4$ ,  $C_2H_2$  are witnessed in common with arcing faults and  $C_2H_2$  need proper monitoring to diagnose arcing failures.



**Partial discharge faults:** With low energy discharges in the initial stages  $\text{CH}_4$  and small traces of  $\text{C}_2\text{H}_2$  increases and at an advanced stage; traces of  $\text{C}_2\text{H}_2$  and  $\text{C}_2\text{H}_4$  raises in mineral oils. In ester fluids,  $\text{H}_2$  and  $\text{C}_2\text{H}_2$  are witnesses. However, severe traces of  $\text{H}_2$  remains common in both dielectric liquids. Hence,  $\text{H}_2$  and  $\text{C}_2\text{H}_2$  may be monitored for identifying low energy discharging activities.

**Thermal faults:** Local hotspots in mineral oil increases  $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_6$ , and  $\text{C}_2\text{H}_2$  whereas in ester oil,  $\text{H}_2$ ,  $\text{CH}_4$  and  $\text{C}_2\text{H}_6$ , and some  $\text{C}_2\text{H}_4$  increases.

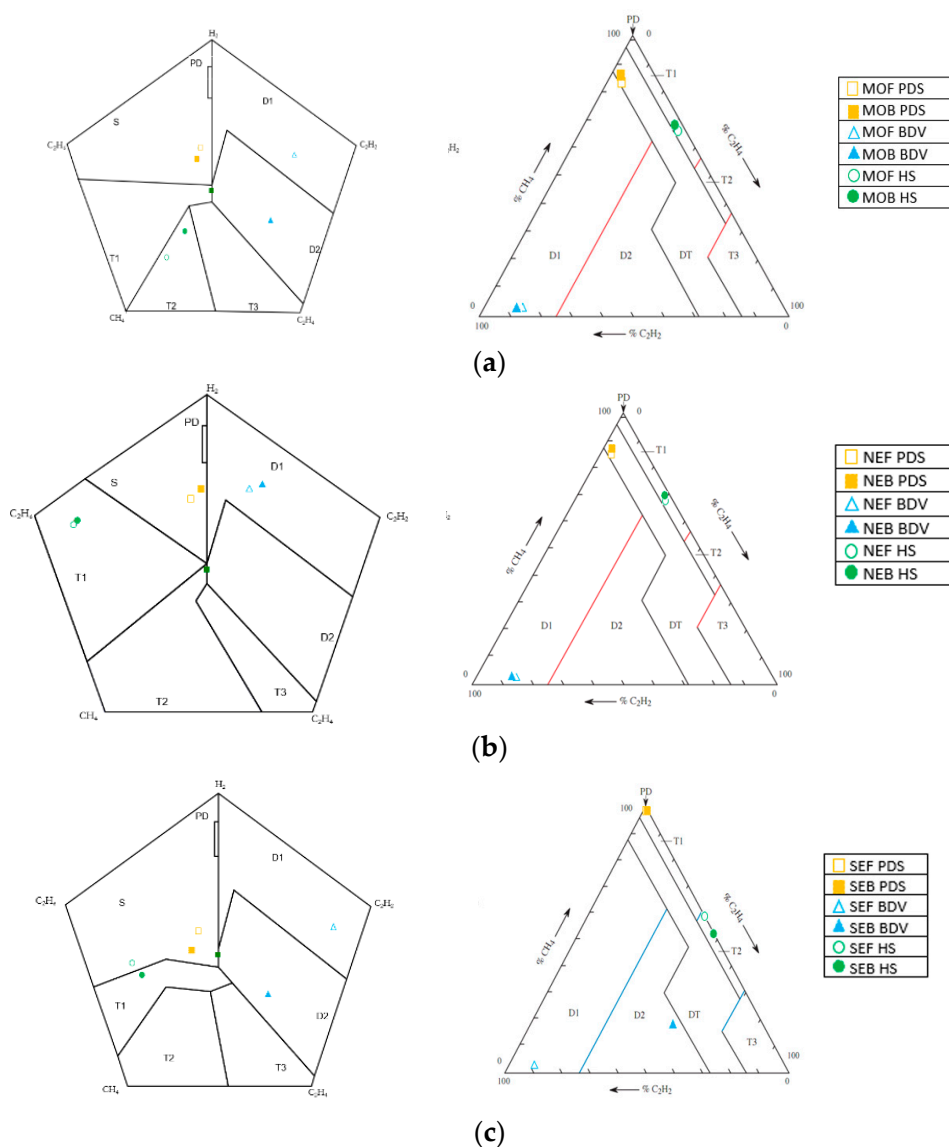
However, electrical and thermal faults are mostly associated with cellulose insulation and degradation of cellulose is accompanied by the generation of  $\text{CO}$  and  $\text{CO}_2$  gases. Hence, the above discussed faults are also mostly witnessed by  $\text{CO}$  and  $\text{CO}_2$  gases for cellulose-based insulation systems. Also, the influence of aging on the gassing behavior is not addressed in the said standards. In the present work, dissolved gas analysis has been performed on fresh and aged mineral oil and ester fluids after subjecting to partial discharges, arcing, and thermal hotspot. Hence, the gases generated under the influence of different faults for a dielectric liquid with aging are discussed in this section. The details of the dissolved gases for different oils under different faults for mineral oil, natural, and synthetic esters are shown in the Figure 5.



**Figure 5.** Illustration of the results of dissolved gases under different fault conditions; (a) mineral oil; (b) synthetic ester; (c) natural ester; (d) total dissolved combustible gases.

It is noticed that, the concentration of the majority of the gases is higher in case of aged oil under the influence of thermal and electrical faults. For arcing faults,  $\text{H}_2$ ,  $\text{CH}_4$ , and  $\text{C}_2\text{H}_2$  are found to increase in all the dielectric fluids. However,  $\text{O}_2$  is reduced and significant change is not noticed in the traces of  $\text{N}_2$  for fresh and aged oils. Thus,  $\text{H}_2$ ,  $\text{CH}_4$ , and  $\text{C}_2\text{H}_2$  gas concentrations vary with the state condition of the oil under arcing faults for mineral oils and non-mineral oils. For partial discharge faults, a much less change in  $\text{H}_2$  and  $\text{C}_2\text{H}_2$  is noticed for fresh and aged oils. This is because, cellulose decay particles act as a filtering and absorbing medium under low energy discharge fault conditions [27].

However, there is almost no change in  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$  for fresh and aged mineral oil. For ester fluids, a noticeable change in the traces of  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$  are noticed. Therefore, under partial discharging activity,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$  vary with the condition of the ester fluids and  $\text{H}_2$  will be generated in common for both the fluids according to the state of the oil. For thermal faults, there is a significant change in  $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$  in mineral oil while in ester fluids, there is a small change in  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$ . This is because of the fault temperature which is not more than  $400^\circ\text{C}$  and hence a significant change in  $\text{C}_2\text{H}_6$  and  $\text{C}_2\text{H}_2$  are not witnessed. Hence, under thermal faults with less temperatures,  $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$  gases will be generated in common for both the fluids according to the state of the oil. From Figure 5b, it is noticed that, the generation of combustible gasses increase with increasing degradation of the oil. However, the generation of combustible gasses are higher for partial discharging and hotspot activity. This is because, the degradation of dielectric fluids is accelerated by cellulose decay particles, and other conductive particles. Therefore, excessive amounts of  $\text{CO}$  and  $\text{H}_2$  increases easily in any event of the fault, thus aiding to the increase in TDCG. The illustration of Duval's triangle and Duval's pentagon with the fault distribution locations are shown in Figure 6 for mineral oil, natural, and synthetic esters.



**Figure 6.** Illustration of fault gas diagnosis using Duval's pentagon and Duval's triangle methods; (a) mineral oil; (b) synthetic ester; (c) natural ester.

To further understand the influence of the condition of the dielectric liquid on gassing tendencies under different faults, Duval's triangle and Duval's pentagon methods for mineral oil and non-mineral oils have been applied for mineral oil and ester fluids respectively. Both fault diagnosing methods indicate that faults evolve with degradation duration. However, this phenomenal changing depends on the intensity of fault and the degradation rate of the insulation system. The insulation system degradation rate is highly dynamic and hence the gassing tendency of the dielectric fluid remains dynamic with operation time. Because as per Duval's methods, any disagreement or mismatching in the fault type using triangle and pentagon methods indicate the presence of more than one fault [28]. Such a measurement requires more investigations to diagnose the fault. To illustrate changes of fault gas, both diagnosing methods and authors' observations on fault matching have been summarized in Table 5. It is to be noticed that, there is a high disagreement between all partial discharge fault samples for all the dielectric fluids. It is to be recalled that, in the present study, a spark is discharged on the surface of the liquid applying 9 kV voltage for five hours. The stray gassing is noticed for fresh dielectric fluids in case of partial discharging activity of the present study. One may understand that even minor partial discharging activities with low energy and for short durations will lead to stray gassing and involves in local temperature raise. To further comment on this, a detailed study on the type of fault diagnosis for partial discharges with different energy levels and different types (surface discharge, internal discharge, and corona discharge) is required. For arcing faults, the fault diagnosis matched for fresh samples (mineral oil, and ester fluids). However, aged mineral oil does not match but the similarity may be accepted as they are electrical discharge faults with different intensities. This is due to the aging impact; it is to be recalled that cellulose decay particles have been manually added to get the required acidity values.

It is known that the degradation of cellulose is much higher in mineral oils as compared to ester fluids. Hence, these decay particles added to the oil, differently influence the oil with arcing when compared to the ester fluids. Hotspot simulation faults almost matched or partially matched for all samples. However, fresh natural ester confined to stray gassing while aged natural ester result in thermal fault in case of Duval's pentagon whereas aged oils confined to thermal faults.

It is to be mentioned that care is taken during the experimentation to avoid interaction of the liquid with external air. Albeit all the three setups are hermetically sealed, a neck headspace is allowed in the test cells. This neck headspace is facilitated for the safety purposes, oil expansion, and to easily accommodate the bubble pressure created. Thus, there is a scope for the fault gasses to escape in the gas phase too. The above results are inclusion of only the fault gas that is dissolved in the liquid phase. To understand the gases in the gas phase, Ostwald solubility coefficient ( $L$ ) of different gasses presented in IEEE Std C57.104 are used. The details of the Ostwald coefficients, gas phase gasses, liquid phase gasses, and total gas generation are presented in the Table 6.

It is to be mentioned that, the details of Ostwald solubility coefficients in case of ester fluids are not yet reported in IEEE Std C57.155. Therefore, for illustration purposes the coefficients reported in IEEE Std C57.104 have been used in the present study. Further, it is already arguable for the use of single Ostwald coefficient even for mineral oil as the aging of oil affects the partial pressure of the gases. Therefore, it will be quite difficult to justify the use of a single Ostwald coefficient for both mineral and ester liquids. Hence, it is to be understood that, the changes/variations in the gassing tendency in different liquids at different aging conditions may also be attributable to these factors. The details of accuracy and repeatability of individual gases measurements are provided in Table 7.

**Table 5.** Fault diagnosis details for Duval's triangle and Duval's pentagon.

Sample	Fault Diagnosis by Duval's Pentagon		Fault Diagnosis by Duval's Triangle		Fault Matching
	Code	Fault	Code	Fault	
MOF BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
MOA BDV	D2	Electrical discharges of high energy	D1	Electrical discharges of low energy	Partially matched (electrical discharges)
MOF PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Not matched
MOB PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Not matched
MOF HS	T2	Thermal faults between 300 and 700 °C	T1	Thermal fault of less than 300 °C	Partially matched (Thermal)
MOB HS	T2	Thermal faults between 300 and 700 °C	T1	Thermal fault of less than 300 °C	Partially matched (Thermal)
NEF BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
NEB BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
NEF PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Not matched
NEB PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Not matched
NEF HS	T1	Thermal fault of less than 300 °C	T1	Thermal fault of less than 300 °C	Matched
NEB HS	T1	Thermal fault of less than 300 °C	T1	Thermal fault of less than 300 °C	Matched
SEF BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
SEB BDV	D2	Electrical discharges of high energy	D2	Electrical discharges of high energy	Matched
SEF PDS	S	Stray gassing	T1	Thermal fault of less than 300 °C	Not matched
SEB PDS	S	Stray gassing	T1	Thermal fault of less than 300 °C	Not matched
SEF HS	S	Stray gassing	T2	Thermal faults between 300 and 700 °C	Not matched
SEB HS	T1	Thermal fault of less than 300 °C	T2	Thermal faults between 300 and 700 °C	Partially matched (Thermal)

**Table 6.** Details of total gas generation at different fault conditions in various liquids.

			Dissolved Gas in Liquid Phase (ppm)						Dissolved Gas in Gas Phase (ppm)						Total Gas Generated (ppm)					
		L	MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB
H2		0.0429	125	299	10	195	1220	1140	2914	6970	233	4545	28438	26573	3039	7269	243	4740	29658	27713
CO		0.9	10	1083	34	1490	907	760	11	1203	38	1656	1008	844	21	2286	72	3146	1915	1604
CO2		0.102	558	3176	1243	5320	6660	4810	5471	31137	12186	52157	65294	47157	6029	34313	13429	57477	71954	51967
CH4		0.337	31	319	192	983	397	359	92	947	570	2917	1178	1065	123	1266	762	3900	1575	1424
C2H4		1.35	68	1446	19	1540	23	16	50	1071	14	1141	17	12	118	2517	33	2681	40	28
C2H6		1.99	4	125	1	198	215	67	2	63	1	99	108	34	6	188	2	297	323	101
C2H2		0.938	492	1113	192	983	61	48	525	1187	205	1048	65	51	1017	2300	397	2031	126	99
H2		0.0429	1910	1527	1330	1390	1220	1140	44522	35594	31002	32401	28438	26573	46432	37121	32332	33791	29658	27713
CO		0.9	459	649	992	1280	907	760	510	721	1102	1422	1008	844	969	1370	2094	2702	1915	1604
CO2		0.102	4114	6724	8840	16100	6660	4810	40333	65922	86667	157843	65294	47157	44447	72646	95507	173943	71954	51967
CH4		0.337	1004	1018	1080	1520	397	359	2979	3021	3205	4510	1178	1065	3983	4039	4285	6030	1575	1424
C2H4		1.35	10	11	3	6	23	16	7	8	2	4	17	12	17	19	5	10	40	28
C2H6		1.99	100	100	145	235	215	67	50	50	73	118	108	34	150	150	218	353	323	101
C2H2		0.938	16	23	24	27	61	48	17	25	26	29	65	51	33	48	50	56	126	99
H2		0.0429	37	225	49	48	60	150	862	5245	1142	1119	1399	3497	899	5470	1191	1167	1459	3647
CO		0.9	1375	1600	2100	4112	465	783	1528	1778	2333	4569	517	870	2903	3378	4433	8681	982	1653
CO2		0.102	2053	2141	4601	9566	1870	2340	20127	20990	45108	93784	18333	22941	22180	23131	49709	103350	20203	25281
CH4		0.337	404	1333	424	851	24	36	1199	3955	1258	2525	71	107	1603	5288	1682	3376	95	143
C2H4		1.35	120	1471	284	755	11	15	89	1090	210	559	8	11	209	2561	494	1314	19	26
C2H6		1.99	97	1259	1154	1773	1020	1930	49	633	580	891	513	970	146	1892	1734	2664	1533	2900
C2H2		0.938	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2

**Table 7.** Accuracy and repeatability details of the individual gasses.

Gas	Accuracy	Repeatability
H <sub>2</sub>	±0.5 ppm or ±5%	±0.5 ppm or ±3%
O <sub>2</sub>	±500 ppm or ±15%	±500 ppm or ±10%
N <sub>2</sub>	±2.000 ppm or ±15%	±2.000 ppm or ±10%
CO	±10 ppm or ±5%	±10 ppm or ±3%
CO <sub>2</sub>	±15 ppm or ±5%	±15 ppm or ±3%
CH <sub>4</sub>	±0.2 ppm or ±5%	±0.5 ppm or ±3%
C <sub>2</sub> H <sub>2</sub>	±0.2 ppm or ±5%	±0.5 ppm or ±3%
C <sub>2</sub> H <sub>4</sub>	±0.2 ppm or ±5%	±0.5 ppm or ±3%
C <sub>2</sub> H <sub>6</sub>	±0.2 ppm or ±6%	±0.5 ppm or ±4%

#### 4. Conclusions

The influence of the condition of the dielectric fluid on gassing has been reported for mineral oil, natural, and synthetic esters under electrical and thermal faults. The degradation under fault conditions has been reported using dissolved decay contents, absorbance, and turbidity. The dissolved gas analysis by the application of Duval's fault gas diagnostic methods are adopted to understand the gassing behavior of the dielectric fluids. It is inferred that, fault gases in a transformer evolve with respect to degradation of the dielectric fluid. As degradation of the fluid is highly dynamic with operating times, there is a need to understand the gassing tendency of an insulation liquid vis-à-vis aging markers. It is also found that, the concentration and type of dissolved gasses generated depend on the type of fault. In other words, the gassing tendency and fault gasses will not be the same for a similar type of fault at different fault durations and fault energy. The theoretical premise that aging by-products affects the gassing tendency and DGA is experimentally confirmed. The results reported in this study should be helpful in further improving the dissolved gas analysis of ester filled transformers. Dissolved gas analysis is a potential fault diagnosing tool having a large variance in the research results reported by various researchers across the globe. Thus, demanding need to emphasize the research on dissolved gas analysis of alternative dielectric fluids at different aging conditions, different fault intensities, and fault durations.

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